A PHOTOELECTRIC DEVICE FOR THE RAPID MEASUREMENT OF LEAF AREA[1]

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Various methods involving the use of light-sensitive cells as reported by Gerdel and Saulter,[2] Bergman,[3] and others for the determination of leaf area have been described. Most of these methods are based on the use of systems of lenses to secure uniform distribution of the light flux over the aperture upon which the leaves are placed.

The use of lens systems to distribute the light from a single source has two inherent limitations aside from the expense. The amount of energy received by the cell or cells is largely limited by the intrinsic brilliancy of the light source, and therefore necessitates the use of sensitive nonportable galvanometers. The size of the lenses employed also sets a definite limit on the size of aperture which can be uniformly irradiated.

The apparatus to be described in this paper was designed to eliminate the difficulties of optical systems employing large lenses by placing the leaves on a ground-glass diffusing screen and irradiating the diaphragm upon which the screen is set with a highly diffused, uniformly distributed source of radiation.

This method is based on the following theoretical considerations: A group of thin opaque objects such as leaves of a total area A is placed upon and in the same plane as a perfect diffusing screen diaphragmed to a known circular area A_o. The aperture of the diaphragm is irradiated from above by a source of such a flux distribution that the intensity of the flux leaving the ground-glass diffusing screen and reaching the sensitive cells is of the same value at all points of the aperture. When this condition exists, the decrease in response of a linear light-sensitive cell, such as a vacuum photoelectric cell, will be proportional to the opaque areas on the aperture of the ground-glass diffusing screen. The following relationship will then obtain:

$$A = LK(I_o - I)$$

$$A_o = KI_o \text{ when } I = 0$$

Where

A_o = Area of diaphragm of diffusing screen

A = Area of leaves

I_o = Photoelectric current with full aperture of the diaphragm

I = Photoelectric current with leaves in place

K = Constant relating photoelectric cell current and area

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[1] Received for publication Jan. 18, 1935; issued June, 1935.

[2] Gerdel, R. W., and Saulter, R. M., measurement of leaf area using the photoelectric cell. Jour. Amer. Soc. Agron. 20:635–643. ———— 1928.

[3] Bergman, H. F., measurement of leaf areas by means of the photoelectric cell. Report presented at tenth annual meeting Amer. Soc. Plant Phys., Boston, Dec. 30, 1933.

Figure 1 presents in diagrammatic form the details of this instrument, and figure 2 is from a photograph of the apparatus set up for operation.

The illuminator consists of a set of lamp bulbs mounted on an open board above a plate of Florentine or maze glass. The square galvanized-iron housing has a flange at the bottom upon which the glass rests, with a second flange near the top so placed that the lamp bulbs are from 3 to 4 inches above the diffusing glass when the lamp mounting is resting upon it. The lamp mounting consists of 12 receptacles arranged on a board as shown, with a square opening in the center and the corners removed for insuring proper ventilation. The 20 lamp bulbs are mounted in the 12 receptacles by the selection

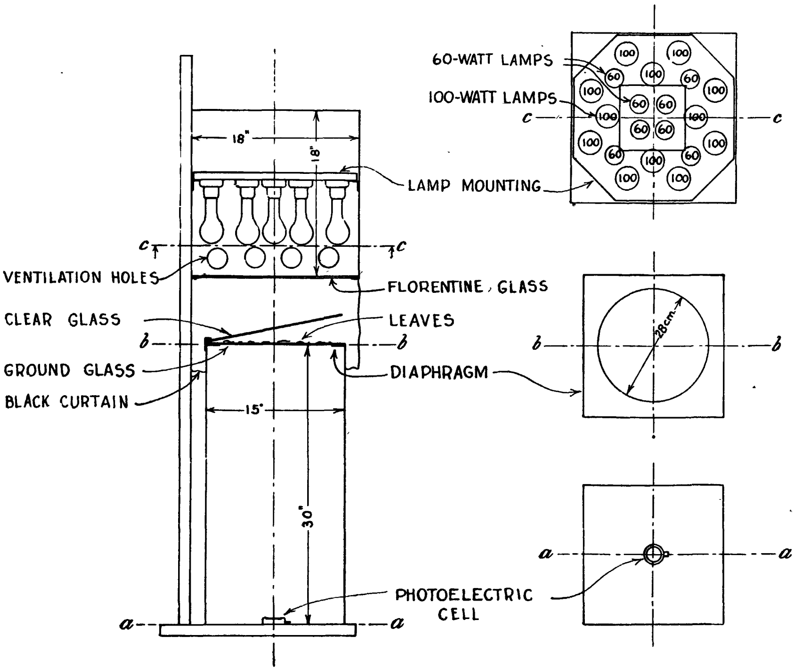

FIGURE 1.—Diagrammatic view of leaf-area apparatus in which a photoelectric cell is used.

of suitable Y and offset double sockets. The use of double sockets is not as satisfactory as small receptacles mounted rigidly on an open metal framework. However, they do lend flexibility to an experimental set-up.

The arrangement is not very critical, the only requirement being that the lamps should be evenly distributed over the area, with the higher wattage lamps around the outside. In this manner, the flux is roughly controlled to give a final distribution which is uniform over the surface of the aperture. The final adjustment is made by raising and lowering the illuminator, which is mounted on a wooden frame above the receiving unit. Ventilation is taken care of by a series of 2-inch holes in the lower part of the housing. This is an important factor and must be given careful consideration, for the apparatus consumes nearly 1,700 watts. The sockets should not have wax plugs around the screws since the heat melts the wax and it runs down onto the bulbs. The inside of the housing may be painted with a heat-resisting aluminum paint which reflects the radiation and prevents the housing from becoming excessively hot.

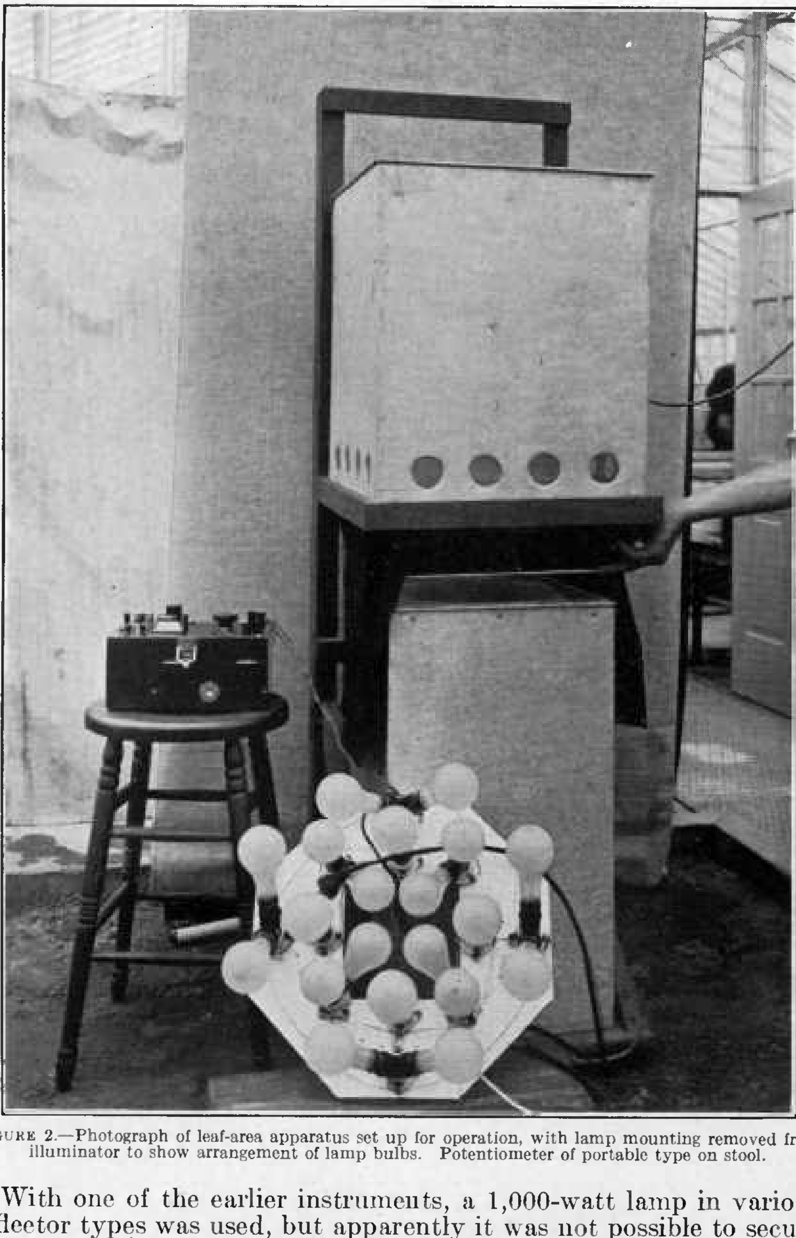

FIGURE 2.—Photograph of leaf-area apparatus set up for operation, with lamp mounting removed from illuminator to show arrangement of lamp bulbs. Potentiometer of portable type on stool.

With one of the earlier instruments, a 1,000-watt lamp in various reflector types was used, but apparently it was not possible to secure the proper distribution of flux with this lamp. A high-wattage lamp would be much more efficient than the lower wattages and much simpler to use if the proper reflector design could be worked out. Such a reflector would need to give a flux distribution that would be lower in the center than around the periphery of the illuminated area in the plane of the glass-diffusing screen.

The lower receiving unit is smaller in section than the illuminator. The aperture as shown in section *b* of figure 1 is 12 inches in diameter. The diaphragm is covered by a pane of ground glass and a pane of clear glass. The leaves are placed between the two panes and in contact with the ground surface. A flange soldered on the rear of the diaphragm facilitates raising and lowering the clear glass pane for insertion of the leaves.

The light-sensitive unit is mounted in the base. One or more cells may be employed. However, the use of three or more cells increases the over-all accuracy of the instrument, and also makes it possible to install a less sensitive galvanometer. The use of many cells allows a certain degree of adjustment for nonuniform flux distribution, by adjusting the distance of the cells from the aperture and the distance of the cells from one another. It also makes it possible to mount them quite close to the aperture and thus greatly reduce the height of the apparatus.

The determination of flux distribution is made by passing an opaque diaphragm with a small opening over the aperture. It has been found that if the reading on a galvanometer in the cell circuit does not vary more than 10 percent as the opening is moved over the aperture, the resultant accuracy of the entire apparatus will be from 1 to 2 percent of the actual area for areas of from 100 to 500 cm^2 when a single Weston photronic cell and a small portable galvanometer and potentiometer are used. The control of flux distribution is largely made by raising and lowering the illuminator.

The apparatus is calibrated by taking readings with a series of square or circular pieces of opaque material such as thin metal or black bakelite. These pieces are of known areas. With these data and the value of A_0 and I_0, a calibration curve can be drawn relating area and photoelectric current.

In practice, the instrument should be calibrated every time the value of A_0 has changed appreciably. The calibration requires only a short time and serves to check the changes in line voltage. Under conditions of seriously fluctuating line voltage, it may be advisable to recalibrate with a few known areas with each area measurement. If the line voltage is constant and the apparatus has had 20 to 30 minutes to come to equilibrium, the A_0 reading will remain constant for long periods. The use of a voltmeter in the line supplying power to the lamps is not of much value, since a change in voltage sufficient to vary the voltmeter reading very slightly will produce a large change in visible radiation emitted by the lamps. The constancy of the electromotive force generated by the light-sensitive cell is the best indication of steadiness of line voltage.

If the response of the cell is not strictly proportional to the intensity of the light falling upon it, the foregoing relationships do not hold and the calibration curve will not be a straight line having a negative slope, but will be somewhat curved. A pair of typical calibration curves exhibiting the linear and nonlinear conditions is shown in figure 3.

These curves were taken with a potentiometer across a photogalvanic type of cell (Weston photronic). In the first case, the cell is operating with a resistance of 50 ohms shunted across it, thus making the response essentially linear. In the second case, no current is flowing through the cell, and the result is the curved or nonlinear voltage response.

The voltage response of the photogalvanic type of cell is high and the internal resistance is relatively low as compared to the photoelectric cell. This makes it well adapted to potentiometric measurements. However, these cells have two unfortunate characteristics. They have a very nonlinear voltage response, the electromotive force falling off from a straight line with increasing light intensities and the curve approaching an asymptote at high values. If a low resistance of less than 50 ohms be placed across the cell, the response becomes essentially

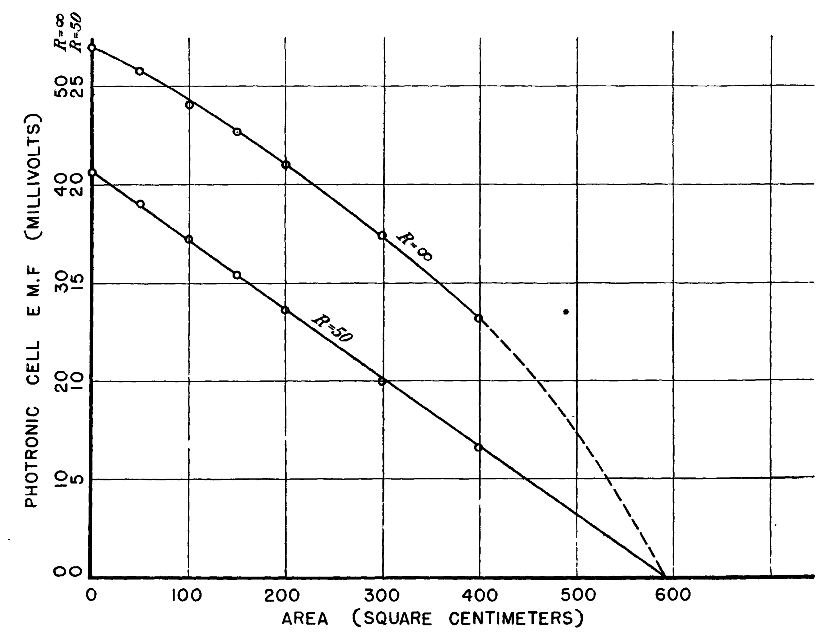

FIGURE 3.—Calibration curves of leaf-area apparatus, showing linear and curved type of responses. *R* is value of resistor across photronic cell.

linear for low light intensities due to the change in internal resistance with light intensity. However, the internal resistance reaches equilibrium rather slowly, and in some cases the last few percentages of change require several minutes to reach their final value. This makes the cell entirely too sluggish for precise work when operating under linear conditions. When a low resistance is used across the cell, the external electromotive force is very greatly reduced, in some cases as much as 90 percent. This adds further to the difficulty of reading. Therefore, it is generally more convenient to use a potentiometer, the reading of which is not influenced by the resistance of the cell.

The output of the photogalvanic type of cell may also be read directly with a sensitive microammeter of fairly low resistance, as is done in the case of some of the direct reading illuminometers which have recently appeared upon the market. With one of these illuminometers or a combination of several photogalvanic cells and a suitable microammeter, the apparatus may be very conveniently calibrated in microamperes or foot-candles.

For the precise determination of area, the use of one or more vacuum photoelectric cells is to be recommended. Under these conditions, the radiation from the Mazda lamps should be more highly and uniformly diffused by the use of two or more layers of diffusing glass spaced an inch or two apart. The modern, well-designed vacuum photoelectric cell, when properly used, is stable and linear in its characteristics. Its main disadvantages lie in the necessity for use of highly sensitive galvanometers or vacuum tube amplifiers.

The leaves of many plants are not, even for practical considerations, entirely opaque and some light passes through them. Thus the areas as read from the calibration chart are incorrect, being lower than the actual value. Therefore, a correction factor must be applied. If the leaves being measured have an average total transmission of T for the light source and cell used, and A' is the observed area, the true area A can be shown to have the following value:

$$A=\frac{A'}{1-T}$$

Thus, the true area is the observed area divided by the absorption of the leaf, the latter often being considerably less than unity.

The light transmitted by most leaves as measured by a photogalvanic type of cell with Mazda lamps for a source varies between 0.05 and 0.15 of the incident light. The transmission may be very conveniently determined by removing the cell from its mounting and placing it in a box of opaque material having a small hole in the lid of such a size that one of the leaves to be studied will readily cover the entire opening. This box is placed on the diaphragm beneath the lamp sources and two readings are taken, one with the leaf in place and one without the leaf. This should be repeated several times and the average of the ratio of each pair of recordings determined. The ratio is the transmission T. For these values, it is essential that the cell be operating under linear conditions.

In order to give an idea of the range of magnitude, the following transmission values of a few typical leaves of greenhouse crops, obtained with a Weston photronic cell, are presented:

Plant:	Transmission T	Plant—Continued.	Transmission T
Aster	0.07	Rose	0.06
Calendula	.08	Stock	.06
Leaf lettuce	.07	Sunflower	.10
Nasturtium	.10	Sweetpea	.10
Pansy	.06	Tomato	.12

It is, of course, to be expected that these values are influenced to a large degree by growing conditions. Thus, for each group of determinations, a new value needs to be obtained. Since the correction factor seldom alters the reading more than 15 percent, it is not necessary to determine the transmission of more than a few leaves with a high degree of accuracy.

Leaves are generally quite irregular areas with a large ratio of periphery to area. Therefore, it was thought that an edge effect might be present which would make the apparent area of a large number of irregular small surfaces different from that of one large surface of equal area. To test this possibility, a square piece of opaque black paper of 400 cm^2 area was placed on the diaphragm and a reading taken. The paper was then cut into a large number of small irregular pieces to simulate leaves and a reading again taken. The test was repeated several times and in no case did the second reading differ from the first by more than a few percent. This indicates that no appreciable edge effect exists.

Although the apparatus which has just been discussed is suitable only for detached leaves, it would be readily possible to adapt the same principles to the design of a small portable unit for measuring leaves on the plant. Such a device could be made with a pair of 45-degree mirrors so placed that the Mazda lamps and the photoelectric cells would not interfere with the remaining portion of the plant.

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